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Experimental characterization of the influence of lateral pass width on results of a ball burnishing operation

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Abstract

Ball burnishing has proved to be a highly effective mechanical finishing process of industrial workpieces, because of the excellent surface roughness and fatigue performance that induces in treated workpieces. In order to obtain specific target results from this complex plastic deformation process, its parameters must be accurately controlled. This paper focuses on the influence of the lateral pass width on the average surface roughness of aluminum 2007. Two values of lateral pass width are tested, with two control variables: number of burnishing passes and applied burnishing force. Furthermore, the ball burnishing operation is performed with two different tools: a conventional non-assisted ball-burnishing tool, and a vibrations-assisted one. The most suitable lateral pass width proves to be the distance between the highest peak and lowest vale of the P-profile of the burnishing path, and significantly better results are obtained by assisting the process with vibrations. At the end of the paper, values for lateral pass width for each group of operation conditions are recommended.

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Keywords: ball burnishing; lateral pass width; aluminum; pile up; plastic deformation.

1. Introduction

Burnishing is a mechanical finishing treatment, performed on workpieces to enhance their mechanical properties, and improving their performance to highly demanding working conditions [1]. As other surface finishing treatments, such as lapping, honing, grinding or polishing, burnishing enhances substantively the surface roughness and micro-

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hardness of the objective workpiece, enhancing its performance and reducing friction and wear on parts working in highly demanding regime. Nevertheless, burnishing has a special characteristic that differentiates it from the other mentioned processes, that is, residual compressive stresses are induced in the workpiece surface through several passes of the burnishing tool, thus enhancing the fatigue performance of the piece, and inhibiting the origin of cracks and notches on parts [2].

The operation is performed with a burnishing tool, attached to a conventional machine tool or a CNC machine, with different set-ups depending on the geometry of the workpiece or the design of the tool itself. The tool transmits a controlled force through an indenter located in its tip, and glides on the objective surface with a certain feed velocity. At a microscopical level, through the movement of the ball, the peaks of the P-profile fill its vales, and make the roughness of the surface more uniform, decreasing its average roughness. For this paper, a ball-burnishing tool was used, that is, the indenter is a sphere, in contraposition with other tools in which the deforming action is performed by a cylinder.

Although burnishing is a well characterized process, not all materials react to this process uniformly. One of the main effects of burnishing a surface is the flow of material towards the boundaries of the burnishing path, what is called the piling up of the material (Fig. 1). Pile-ups has influence on how a burnishing operation should be performed to attain a high quality final surface. Burnishing consists on consecutive and parallel passes of the burnishing ball along the objective surface, in a repetitive operation. The ball describes a rectilinear path, then the tool moves a certain distance at its right angles, on the order of microns, to prepare for the next pass, and then executes it. The process would continue repetitively until the whole desired surface is treated. The intermediate step between one pass and the other is defined by the lateral pass width, objective of this study.

Considering the pile-up effect, and the way the burnishing is performed, many authors have investigated about the influence of the lateral pass width on the burnishing result. Depending on the values of this parameter, the tool will have to deform a less or more hardened material [3, 4]. That way, if the lateral pass width is bigger than the width of the effective contact surface of the ball and the surface, it will not affect the results of the process. On the contrary, if the lateral pass width is shorter than the contact surface, each pass will partially act on an already hardened path, due to the previous plastic deformation. That way, assessing the value of the lateral pass width can affect the burnishing process and improve its results and productivity.

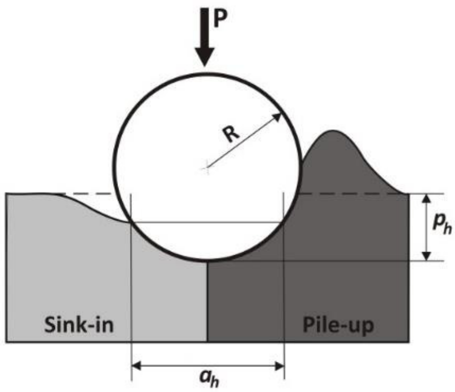

Fig. 1. Diagram of the contact of the burnishing ball and the material surface, and representation of pile-up effect, where ah is the path width, ph is the path depth, R is the ball diameter and P is the applied load.

The importance of studying the lateral pass width in a burnishing process lies also in the fact of the already introduced pile-up effect present in some materials, for successive passes will be applied on previous accumulations of flowed material. The causes and ways in which a burnished surface may pile up is multifactorial. One of the influential aspects is the self-hardening ratio of the material. Gao proposed an analytic solution for the problem of the self-hardening of a spherical object during its plastic deformation due to internal pressures [5]. This solution incorporates the geometry of the indenter, which is proved to be another influencing factor. That was also stated by

Gao et al. [6]. Other authors incorporate in the discussion, the influence of the yield limit of the material or the presence of residual stresses in the initial stock [7].

Nevertheless, most of the authors accept that the main parameter describing to what extent a material piles up, is the self-hardening ratio, n, so that when $n > 0.25$, the material experiences this effect [8]. The aluminum used for the present investigation has $n = 0.26$, and therefore, the piling up phenomena is present. The importance that the self-hardening ratio has acquired in the issue of indentations and plastic deformation by burnishing, has also transcended in finding a geometrical correspondence. That is the case of the c^2 parameter (Eq. 1). For small depths, c^2 is the relationship between the contact area and the total depth of penetration of the indenter represented in Figure 1. Therefore, the c^2 parameter is also a valid descriptor of the grade of pile-up or sink-down present during the indentation, so that piling-up is present when $c^2 > 1$.

$$c^2 = \frac{a_h^2}{2Rp_h} \tag{1}$$

Many researchers have tried to establish a relationship between c^2 and n, through different approximations represented in Figure 2. Although the results are slightly difference, the existence of a certain relationship between both approaches to pile-up prediction is noticeable.

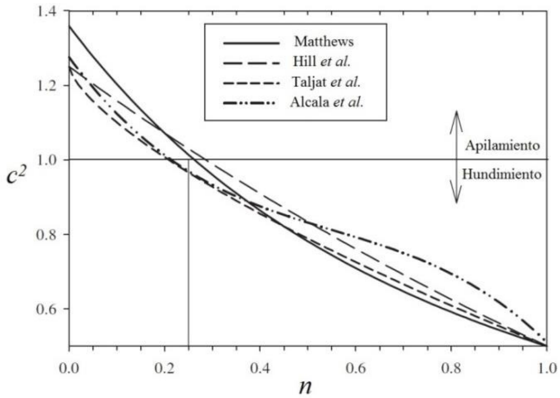

Fig. 2. Evolution of c2 in function of n according to several approximation methods [8]

As shown above, and due to the lack of information in this respect, the authors have considered interesting to develop an experimental plan to investigate the influence of lateral pass width on the final surface roughness results of ball-burnishing on an aluminum specimen. As a secondary objective, the effects of assisting the ball-burnishing process with vibrations will be assessed, comparing the resulting roughness with that obtained with the conventional process.

2. Materials and methods

Two specimens of aluminium 2007 were used. One of them was burnished following a conventional non-vibrations-assisted ball-burnishing process (NVABB), and the other one was subjected to a vibrations-assisted ball-burnishing process (VABB). In both cases, specimens were pre-processed with a face milling operation, performed with a spindle of 3000 min^{-1}, a feed of 330 mm/min and a depth of cut of 0.5 mm. The specimens were then grinded with a P1200 disc and polished with diamond paste of 9 µm. That way, all the burnishing operations were performed from the same starting point in terms of surface roughness and tensile residual stress. This is a very important fact, because burnishing results are not only a result of a certain combination of process parameters, but also highly dependent on the initial surface conditions. Therefore, both specimens had a starting measured surface roughness of $Ra = 1.5914$ µm and $Ra = 1.3886$.

The burnishing tool was attached to a CNC LAGUN MC600 machine, and the operations were executed with a feed of 600 mm/min. Three control variables were taken into account: number of passes (*n*), burnishing force (*F*) and lateral pas width (*b*), at three, two and three levels respectively (Table 1). Therefore, eighteen burnishing operations were developed for each of the two specimens, obtaining one burnishing paths for all the possible combination of control variables.

Table 1. Control variables for the performance of the burnishing operations

Control variables	n	F (N)	b
NVABB	1, 3, 5	60, 90	0, l, lm
VABB	1, 3, 5	60, 90	0, l, lm

The levels of each variable were deduced from several sources. Many authors detect that more than five passes do not cause significant results on the burnished piece [3, 9]. As for the burnishing force, it has been measured through the calibration of the pre-loaded spring part of both tools (Fig. 2c), and has been established from previous experience [10]. How the force is transmitted to the workpiece is explained below.

2.1. Description of the burnishing tool

Figure 2a shows the tool assisted by vibrations used during these tests. The cold plastic deformation is performed by a 10 mm diameter ball made of hardened chrome steel (100Cr6), covering a range of hardness of 55 – 66 HRC. That ball rolls freely during the whole process, independently of the applied deforming force.

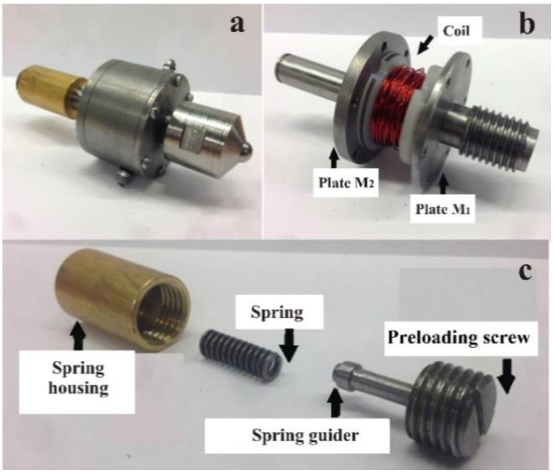

Fig. 3. Ball-burnishing tool assisted with vibrations. (a) Compact tool. (b) Detail of coil that induces vibrations into the system. (c) Parts of the preloading system.

Vibrations come from an external source, namely a coil rolled on the body of the tool (Fig. 3b). The generated magnetic field deflects the M_1 and M_2 plates. A cylindrical cover protects the coil, and is attached to the system between both plaques, responsible for transmitting the vibration to the burnishing ball. By loading the calibrated spring, the transmission of the vibrations are assured. The whole tool is assembled then with an ISO cone, unifying the system and making it move as a single object, and subjected only to the burnishing force defined for the operation.

The tool, designed and developed by Gomez-Gras et al. is therefore a compact system, able to transmit a homogeneous force to the workpiece [10]. It is a flexible system as well, for when the coil is not induced by electrical current, the tool can be used for a conventional burnishing process, like the one performed by commercial tools. Furthermore, the tool can be assisted by the coil and therefore been used for a VABB process. The tool vibrates at a frequency slightly higher as 2 kHz and amplitude of 13 μm.

2.2. Definition of the lateral pass width to be tested

On the other hand, the values of l and l_m were deduced from a previous characterization of the burnishing path in the same conditions, but taking lateral pass width of 0 (Table 2). The previous analysis of the signals resulting from all experiments taking $b = 0$, have evidenced the presence of pile-up, and have originated the definition of l and l_m.

This way, l has been defined as the distance between the highest peak of the pile-up and the lowest point of the burnishing path. On the other hand, lm is half this distance ($l_m = l/2$) (Fig. 4). In other words, what is being tested is whether it is more desirable to burnish just on the top of the piled up material ($b = l$), or approximately in the neutral point of the P-profile of the burnished path ($b = lm$).

Table 2. Values of lateral pass width tested, for each control variables combination

NVABB							
b (mm)		l			lm		
n		1	3	5	1	3	5
F (N)	60	0.250	0.270	0.280	0.125	0.135	0.140
	90	0.270	0.280	0.290	0.135	0.140	0.145
VABB							
b (mm)		l			lm		
n		1	3	5	1	3	5
F (N)	60	0.280	0.290	0.310	0.140	0.145	0.155
	90	0.300	0.320	0.330	0.150	0.160	0.165

The profile of each burnishing paths was taken with a Mitutoyo profilometer, model SURFPAK-SJ V3, with a cut-off length of 2.5 mm. For each of the paths, ten measures were registered, in both senses at their right angles, resulting it twenty measures for each path, and a total of 320 signals for the NVABB specimen and 320 for the VABB one. These signals were process to obtain average measures as reference to.

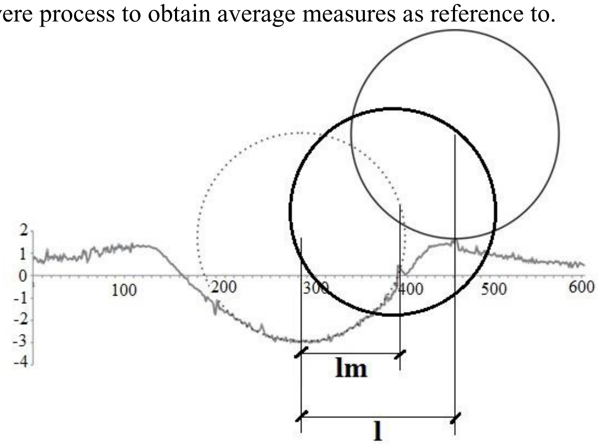

Fig. 4. Representation of l and l_m on the surface of the previously burnished path.

3. Results

Burnishing paths registered with the profilometer have been represented by grouping three signals for each testing combination of variables: the nominal path resulting from burnishing without lateral pass, the path resulting from burnishing taking a lateral pass of l and then the one resulting from burnishing taking lateral pass l_m. Figure 5 shows the path generated by burnishing of a specimen with a 90 N force, 1 pass and assisted with vibrations. Although the profiles generated after burnishing with *b* not zero are clearly more irregular than the one resulting from burnishing repeatedly on the same path, it is noticeable that they result in a more uniform profile. Visual inspection allows to state that the flattest surface is the one generated by a lateral pass width of *b* = l.

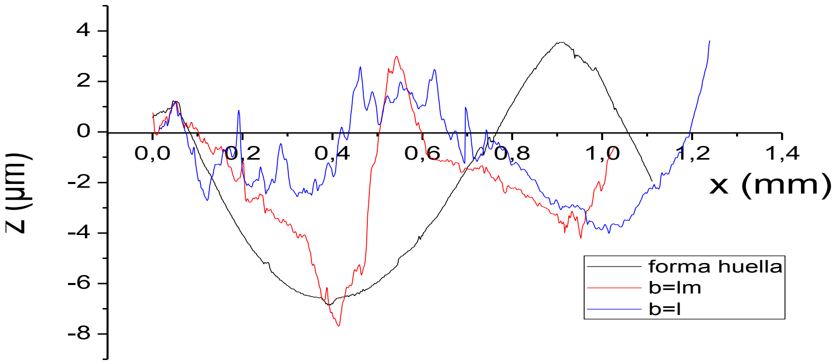

Fig. 5. Representation of l and l_m on the surface of the previously burnished path.

In order to determine more accurately how the improvement in surface roughness is produced, the parameter of average surface roughness has been used. The definition of this parameter itself allows establishing an arithmetical relationship between the lateral pass width and surface roughness results (Eq. 2). The results of the measures are shown in Table 3.

$$R_a = \frac{1}{lb}\sum_{0}^{lb}\left|Z_{(x)}\right| \tag{2}$$

Table 3. Measured average roughness for both studied lateral pass widths

NVABB				
F (N)	60		90	
n / b (mm)	l	lm	l	lm
1	0.9240	1.0193	0.7571	0.8214
3	0.9114	1.0060	0.5816	0.7122
5	0.8615	0.9915	0.5243	0.6611

VABB				
F (N)	60		90	
n / b (mm)	l	lm	l	lm
1	0.7612	0.9543	0.5511	0.6978
3	0.7858	0.8250	0.5813	0.6330
5	0.5931	0.7666	0.4003	0.6601

The resulting measured *Ra* for each of the burnishing conditions ratifies the hypothesis deduced from the superposition of signals exemplified in Figure 5. Most of cases of measured average roughness are better when the burnishing ball describes the burnishing path just on the peak of the pile-up generated in the former burnishing pass ($b = l$). Nevertheless, it is worth mentioning that the change between burnishing with both tested values of b is not considerably different. The slight improvement is enough to state that taking the complete distance peak-valley of the burnished profile is better than taking half of it, and simultaneously reduces the processing time by half, thus optimizing the process.

On the other hand, the bigger the applied burnishing force, the better are the results of measured average roughness. As for the influence of the number of total passes, five burnishing passes result in the best results in terms of *Ra* (Table 3).

It is also remarkable the influence of the assistance of the process with vibrations, for obtained results are improved. Average roughness obtained with one pass, when the tool is assisted with vibrations, is better compared to those obtained with five passes of the conventional process without vibrations. This fact has also a contribution for the reduction of processing time, thus increasing productivity.

4. Conclusions

After performing the described test son aluminum 2007 specimens, the following conclusions have been deduced:

- The lateral pass width is a relevant parameter to define the burnishing conditions, as established in the hypotheses of this paper. In the case of materials such as aluminum, the indentation with the burnishing tool produces a pile-up affecting the optimal value of the lateral pass.
- Measured average roughness are much better when the distance taken by the ball between subsequent burnishing passes coincides with the distance between the peak of the pile-up and the lowest point of the burnishing path (that is, b = l). Performing burnishing passes with smaller lateral passes, would only increase the processing time, decreasing productivity and is therefore not advisable.
- There is significant difference between performing ball-burnishing assisted with vibrations compared to a non-assisted conventional process. The average surface roughness obtained with one pass of the VABB process is similar to that obtained with five passes of the NVABB once. This fact has also influence the processing time, and shows that assisting the process with vibrations improves burnishing operations.

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